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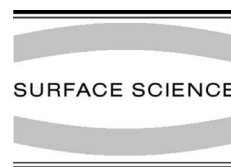
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Non-conformal interface roughness effects on the giant magnetoresistance in magnetic multilayers

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Abstract

We study interface roughness effects on the giant magnetoresistance in magnetic multilayers with non-conformal correlated interfaces. The roughness of each interface is characterized by the roughness exponent H ($0 \leq H < 1$), in-plane correlation length ξ , and rms roughness amplitude Δ . It is shown that the magnetoresistance depends on all the roughness parameters: Δ , H and ξ . The case where the roughness parameters of consecutive interfaces are different due to cross-correlations is also studied. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Magnetic films; Magnetic interfaces; Magnetic phenomena (cyclotron resonance, phase transitions, etc.)

1. Introduction

The giant magnetoresistance (GMR) effect was found in metallic multilayers consisting of alternating ferromagnetic and non-magnetic films [1,2]. The resistance is usually smaller when the magnetic moments of ferromagnetic layers are parallel and larger when they are antiparallel. The GMR effect can be accounted for by taking into account spin asymmetry of the parameters which describe transport properties of the two spin channels (spin dependent scattering probabilities and electronic band structure) [3–6]. Certain complications arise when taking into account electron scattering from interface roughness [7–9].

Experiments indicate that interfaces may have fractal roughness exponents in the whole range

$0 < H < 1$ [10–13]. This can influence GMR in a way that depends on spin asymmetries of bulk and interfacial electron scattering [14]. Up to now theoretical studies of GMR were limited to interfaces which scatter incoherently and ignored contributions from any cross-correlation. In real multilayers, however, some degree of correlation between adjacent interfaces usually exists [10–13]. These cross-correlation effects on GMR will be considered in the present work.

2. Giant magnetoresistance theory for non-conformal rough interfaces

In many situations the GMR effect can be described properly by quasiclassical approaches to the transport phenomena. However, when the electron bulk mean free path is much longer than the sublayer thicknesses, the effect should be described quantum mechanically [15–17]. We assume

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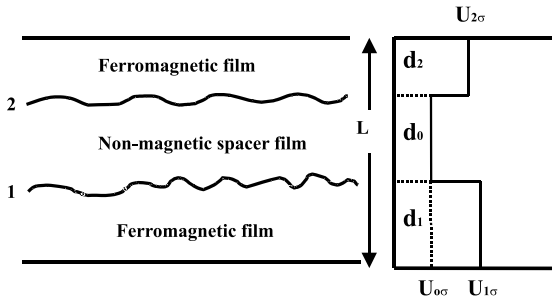


Fig. 1. Tri-layer GMR system and the associated potential well structure.

the spin-polarized free-electron-like model for electronic structure, with the ferromagnetic conduction band being spin-split due to an effective exchange field. We neglect spin-flip scattering processes. Apart from this, we concentrate on interface roughness scattering and therefore neglect scattering by impurities and defects inside the films. Accordingly, we consider two ferromagnetic films of thickness d_1 and d_2 , which are separated by a non-magnetic metallic spacer of thickness d_0 (Fig. 1). The scattering potential of the interface roughness is centered at $z_b^c(\vec{r}) = z_b + (1/2)h_b(\vec{r})$, where $b = 1, 2$ is the interface index, $z_1 = d_1$, $z_2 = d_1 + d_0$, and $h_b(\vec{r})$ describe random roughness fluctuations which are assumed to be a single valued functions of the in-plane vector $\vec{r} = (x, y)$ (by definition $\langle h_b(\vec{r}) \rangle = 0$). For each interface we assume an isotropic autocorrelation function $C_b(r) = \langle h_b(\vec{r})h_b(\vec{0}) \rangle$ and a non-zero cross-correlation function $C_{bb'}(r) = \langle h_b(\vec{r})h_{b'}(\vec{0}) \rangle$ (for $b \neq b'$). For simplicity, the outer surfaces, located at $z = 0$ and $z = d_1 + d_0 + d_2 = L$, are assumed to be perfectly flat. Additionally, we assume the structure is confined by an infinite potential on both sides.

For a particular magnetization configuration, the global in-plane conductivity g , calculated in the Born approximation, is given by [18–20]

$$g = \frac{2e^2}{\hbar L} \sum_{\sigma} \sum_{v=1}^{N_{\sigma}} \sum_{v'=1}^{N_{\sigma}} (E_F - \varepsilon_{v\sigma})(E_F - \varepsilon_{v'\sigma}) [C^{-1}(E_F)]_{vv'} \quad (1)$$

where the matrix elements consist of incoherent scattering C^{in} and cross-correlated scattering C^{cor}

terms, $[C(E_F)]_{vv'} = [C^{\text{in}}(E_F)]_{vv'} + [C^{\text{cor}}(E_F)]_{vv'}$. In Eq. (1) N_{σ} is the number of two-dimensional occupied subbands for spin $\sigma = (\uparrow, \downarrow)$ and E_F is the Fermi energy. The matrix elements $[C^{\text{in}}(E_F)]_{vv'}$ of incoherent term were derived in Ref. [14]. The cross-correlated term $[C^{\text{cor}}(E_F)]_{vv'}$ can be derived in a similar way and one finds

$$[C^{\text{cor}}(E_F)]_{vv'} = \delta_{vv'} Q_{v\sigma}^2 \sum_{m=1}^{N_{\sigma}} P_{vm}^{\sigma} - Q_{v\sigma} Q_{v'\sigma} T_{vv'}^{\sigma}, \quad (2)$$

where

$$P_{vm}^{\sigma} = -2U_{1\sigma}U_{2\sigma}L_{12\sigma}^{vm}F_{12\sigma}^{(1)vm}; \quad T_{vv'}^{\sigma} = -2U_{1\sigma}U_{2\sigma}L_{12\sigma}^{vv'}F_{12\sigma}^{(2)vv'}, \quad (3)$$

$$L_{12\sigma}^{vm} = \prod_{b=1}^2 \psi_{v\sigma}(z_b) \psi_{m\sigma}(z_b) + \frac{1}{16} A_1^2 A_2^2 \prod_{b=1}^2 \psi'_{v\sigma}(z_b) \psi'_{m\sigma}(z_b) + \frac{1}{4} [\psi_{v\sigma}(z_1) \psi_{m\sigma}(z_1) \psi'_{v\sigma}(z_2) \psi'_{m\sigma}(z_2) A_2^2 + \psi_{v\sigma}(z_2) \psi_{m\sigma}(z_2) \psi'_{v\sigma}(z_1) \psi'_{m\sigma}(z_1) A_1^2]. \quad (4)$$

Here, with $U_{b\sigma}$ is the spin-dependent potential step at the b th interface and the following definitions have been introduced [14]:

$$(F_{12\sigma}^{(1)})_{vv'} = \int_{0 < \theta < 2\pi} d\theta \langle |h_{12}(Q_{vv'}^{\sigma})|^2 \rangle, \quad (5)$$

$$(F_{12\sigma}^{(2)})_{vv'} = \int_{0 < \theta < 2\pi} d\theta \langle |h_{12}(Q_{vv'}^{\sigma})|^2 \rangle \cos \theta, \quad (6)$$

where $Q_{vv'}^{\sigma} = (Q_{v\sigma}^2 + Q_{v'\sigma}^2 - 2Q_{v\sigma}Q_{v'\sigma}\cos\theta)^{1/2}$ and $\langle |h_{12}(Q)|^2 \rangle$ is the Fourier transform of $C_{12}(r) = \langle h_1(r)h_2(0) \rangle$.

3. Roughness model

For isotropic self-affine fractals, $\langle |h(q)|^2 \rangle$ has the scaling behavior $\langle |h(q)|^2 \rangle \propto q^{-2-2H}$ if $q\xi \gg 1$ and $\langle |h(q)|^2 \rangle \propto A^2 \xi^2$ if $q\xi \ll 1$ [21–23], with ξ and A denoting the in-plane roughness correlation length and rms roughness amplitude, respectively. The exponent H is a measure of the degree of interface

irregularity at short length scales ($r < \xi$), such that as H becomes smaller the surface becomes more jagged at short length scales ($r \ll \xi$). This scaling behavior is described by the k -correlation model [24,25]

$$\langle |h(Q)|^2 \rangle = (2\pi) \frac{\Delta^2 \xi^2}{(1 + aQ^2 \xi^2)^{1+H}}. \quad (7)$$

The parameter a is given by $a = 1/2H[1 - (1 + aQ_c^2 \xi^2)^{-H}]$ if $0 < H \leq 1$ and $a = 1/2 \ln(1 + aQ_c^2 \xi^2)$ if $H = 0$. Here, $Q_c = \pi/a_0$ is an upper roughness cut-off, with a_0 being of the order of inter-atomic spacing (i.e., ≈ 0.3 nm).

4. Results on giant magnetoresistance for non-conformal interfaces

The GMR effect is described quantitatively by the factor $\text{GMR} = (R_{\text{ap}} - R_{\text{p}})/R_{\text{p}}$, with R_{ap} and R_{p} denoting the resistances in parallel and anti-parallel magnetic configurations, respectively. Our calculations were performed for $E_{\text{F}} = 0.3$ eV, $a_0 = 0.3$ nm, sublayer thicknesses $d_1 = d_2 = d_0 = 2$ nm and for symmetric potential steps $U_{1+} = U_{2+} = 0.1$ eV for the majority electrons and $U_{1-} = U_{2-} = 0.2$ eV for the minority ones. For simplicity, we considered the cross-correlated roughness spectrum to be given as $\langle |h_{12}(Q)|^2 \rangle = [\langle |h_1(Q)|^2 \rangle \times \langle |h_2(Q)|^2 \rangle]^{1/2}$.

The rms interface amplitudes Δ_1 and Δ_2 were chosen such that $\Delta_1, \Delta_2 \ll d_1, d_2, d_0$ for the description based on the first order Born approximation to be valid. For the parameters assumed in Fig. 2, the GMR effect decreases with increasing roughness amplitude Δ_2 (Δ_1 is constant in Fig. 2). However, the presence of cross-correlation weakens the rate of this decrease. Nonetheless, in both cases the GMR effect decreases monotonously with increasing roughness amplitude. There is an apparent contradiction with the GMR dependence on roughness amplitude (Fig. 1) with experimental results by Schad et al. [26] where the opposite behaviour was observed in Fe/Cr superlattices. Such a difference can be attributed to the different form of the cross-correlation function used to analyse the X-ray data, as well as to the fact that during

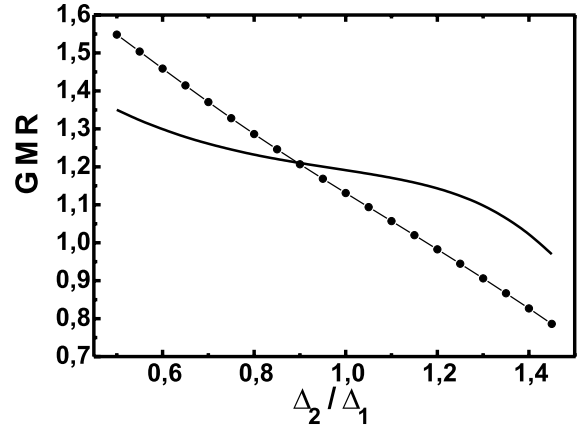


Fig. 2. GMR vs. Δ_2/Δ_1 for $\xi_1 = \xi_2 = 2$ nm, $H_1 = H_2 = 0.8$ and $\Delta_1 = 0.4$ nm. Solid line: with cross-correlation; Line circles: without cross-correlation.

this analysis the same rms roughness amplitude and lateral correlation length assumed for all interfaces of the superlattice [26] (see also Fig. 3).

As follows from Fig. 3, the GMR effect for uncorrelated roughness shows a minimum as a function of increasing correlation length ξ_2 (ξ_1 is constant in Fig. 3). When the interference term due to cross-correlations is included, the monotonic decay of GMR with increasing correlation length is restored. The situation is similar if we consider GMR as a function of increasing interface roughness exponent H_2 as shown in Fig. 4. A

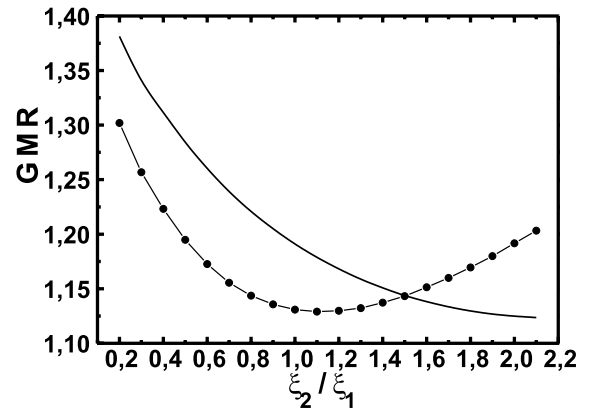


Fig. 3. GMR vs. ξ_2/ξ_1 for $\Delta_1 = \Delta_2 = 0.4$ nm, $H_1 = H_2 = 0.8$ and $\xi_1 = 2$ nm. Solid line: with cross-correlation; Line circles: without cross-correlation.

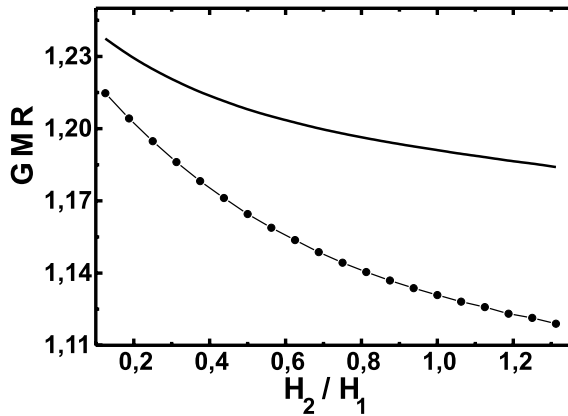


Fig. 4. GMR vs. H_2/H_1 for $\Delta_1 = \Delta_2 = 0.4$ nm, $\xi_1 = \xi_2 = 2$ nm and $H_1 = 0.8$. Solid line: with cross-correlation; Line circle: without cross-correlation.

monotonic decay of GMR takes place at a slower rate in the presence of cross-correlations.

5. Conclusions

The GMR effect as a function of all the three roughness parameters Δ , ξ , and H shows a significant sensitivity to the presence of non-zero cross-correlation between consecutive interfaces. This cross-correlation gives rise to coherent electron scattering by different interfaces, and consequently to an additional term in electronic conductivity. Therefore, in actual experimental systems the precise magnitude of interface roughness parameters as well as the nature of cross-correlations between consecutive interfaces has to be fully characterized, in order to further understand the relationship between GMR and interface microstructure.

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